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Preliminary Trial Design Study of 4th Concept Detector on Geometry, Magnetic Field Distribution and Conductor Material

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There was a suggestion to make the solenoid system of the 4th Concept Detector [1] bigger. The suggested dimensions are as follows,

Inner Solenoid, 7 m diameter and 12 m long with 3.5 Tesla.

Outer Solenoid, 12 m diameter and 14m long.

Responding to this change in the dimensions of the Solenoid System, several simple field calculations were done and reported here.

Design Principle

The basic design principle of Alexander Mikailichenko is inherited, which is composed of the Inner Solenoid, the Outer Solenoid and Wall of Coils Assembly on both Ends [1]. The new dimensions are shown in Fig.1. The detector consists of two major solenoids and several compensation rings. The inner solenoid provides the main flux inside this solenoid. The outer solenoid has a different current direction so that it cancels the field outside the detector. The edge ring at the end of the inner solenoid has the same current direction as the main part of the inner solenoid but has much higher current density. The other six rings at the both ends are also used to cancel field outside the detector.

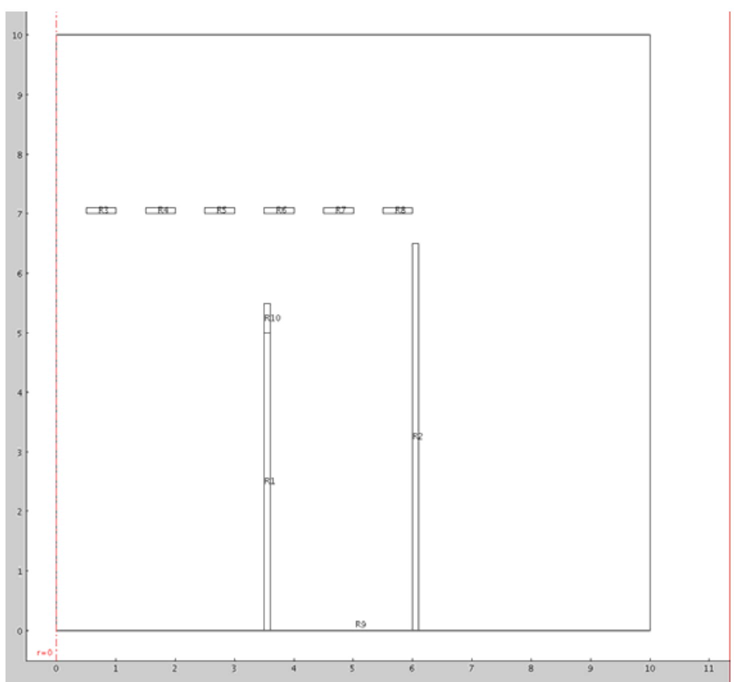


Fig. 1. Dimensions of Solenoid System

The main requirement is to make a quite uniform 3.5 Tesla field region for the central TPC Chamber. There are many parameters which could be changed for this purpose. In order to do this the first thing to be done is to change the current distribution on the inner coil, especially near its ends (Inner Solenoid Edge Ring). Usually the magnetic field at the edges goes up, so we have to select special superconducting material at that location, which works at its field strength.

Superconductor Material

At present time, there is no working High Tc superconductor with high field and high current capacity for a thin walled detector solenoid is commercially available. It might become available in the future.

If the maximum field could be kept below 7 Tesla, we should be able to use NbTi superconductor. This material can be wound on or inside the bobbin. Although the coil has to be epoxy impregnated, but it does not need to be heat treated at high temperature. Its application to the detector solenoid is well established.

For the Edge Ring Coil design with its maximum field less than 12 Tesla, we might be able to use Nb_3Al or Nb_3Sn conductor. These materials have to be heat treated up to 800 C for 15 hours and 650 C for 50 hours respectively. Therefore it needs a large scale oven to fit its size to be made. There are two ways to wind coil, Wind and React, and React and Wind.

The Nb_3Al Rutherford cable, which we are now being developing at Fermilab for accelerator application might be used for this application [2]. The Nb_3Al strand will be used to make Rutherford cable, or other type of cable. The cable might be coextruded with high purity copper, but this technique is not proven yet. Then it will be wound inside a stainless steel bobbin, and heat treated. Finally the conductor and bobbin will be made into an edge ring coil.

Other Considerations

Because of its huge size of the Outer Solenoid, 12 meter in diameter and 14 meter long, we have to consider how to transport it to the final destination from the factory.

Probably parts will be made at the factory, and they have to be assembled on site.

I. First Trial for Maximum Flux Density 10 T

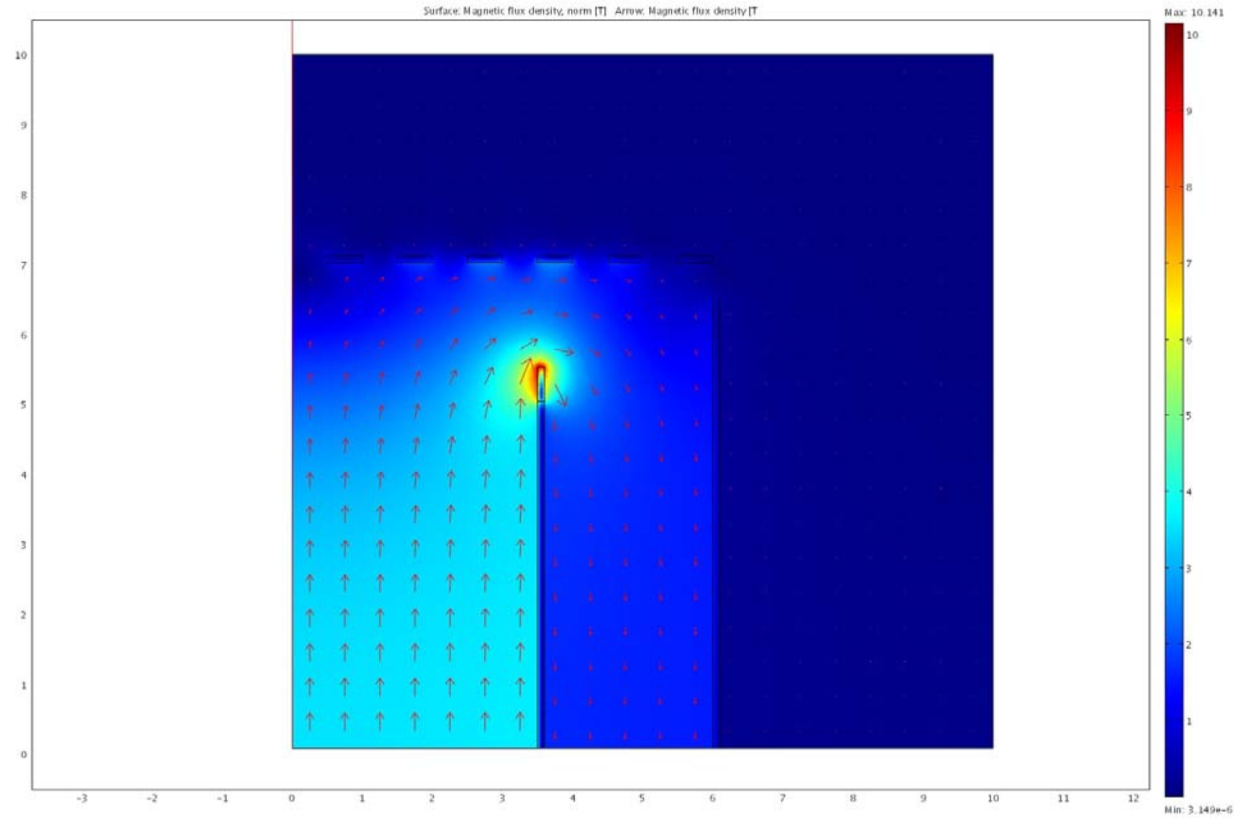
The objective of detector design is to make uniform axial field region as wide as possible over the TPC region: r<1.4 m, |z| <1.5 m.

Superconducting material cannot exceed its critical current density at that flux density. First we take 10 T as the limit. To limit maximum flux density to around 10T, optimization is done. Following result shows the case that current density of the edge ring is four times larger than that of the main inner solenoid. This scheme produces a maximum flux density of 10.14 T.

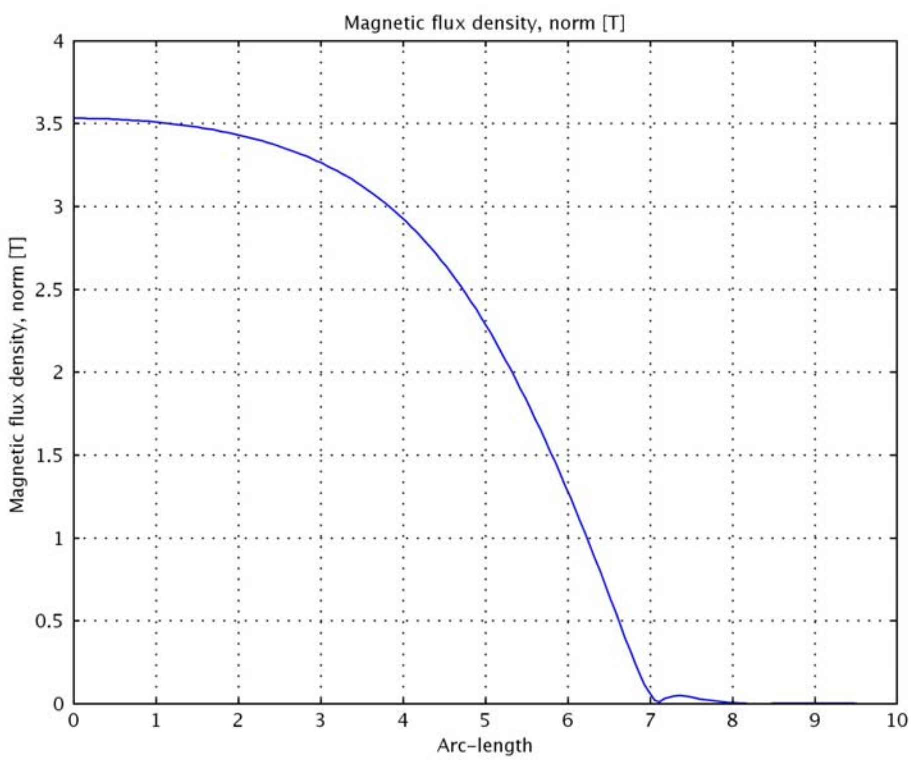
The current density used in this case is shown below.

	Inner Solenoid	Edge Ring	Outer Solenoid	R3	R4	R5	R6	R7	R8
Current Density ($10^6 A/m^2$)	33.6	126	10.77	-8.4	-21	-25.2	-29.4	-16.8	-4.2
Current in segment ($10^6 A$)	21	6.3	7	-0.42	-1.05	-1.26	-1.47	-0.84	-0.21

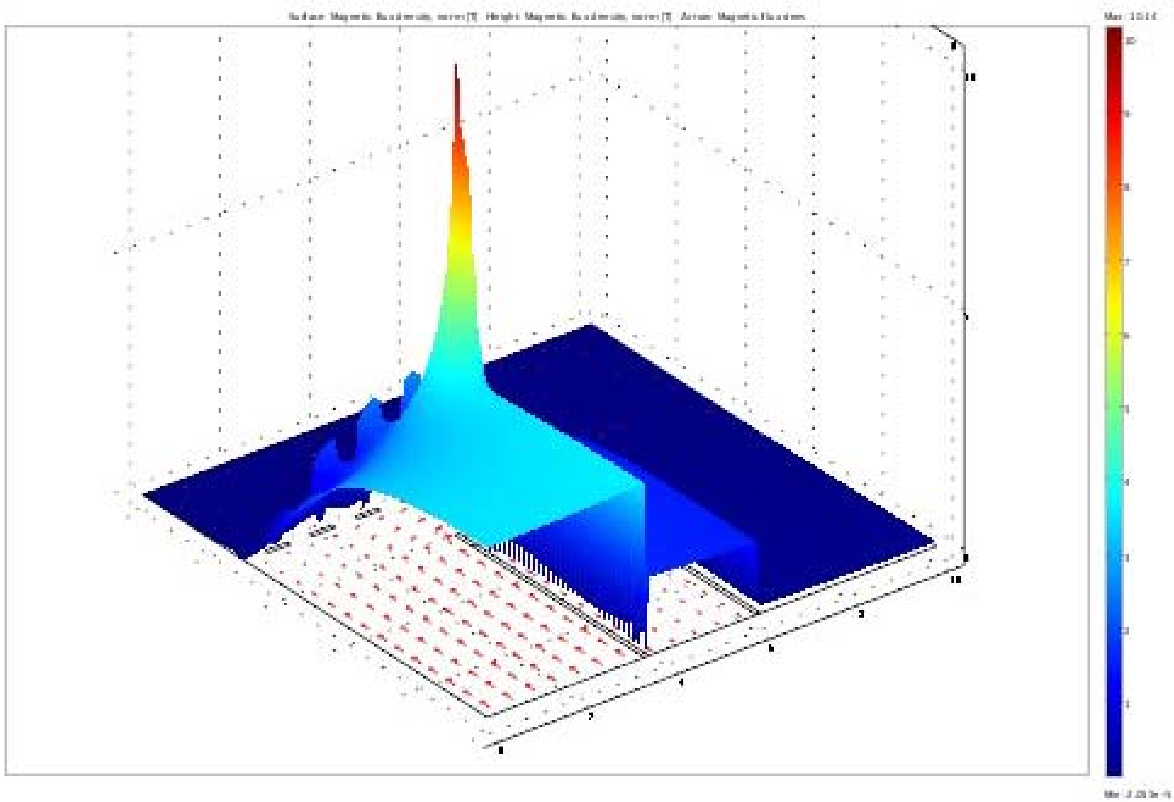
The maximum flux density is 10.1 T.



Field Distribution



Bz on the solenoid z-axis.



3-D Field Distribution

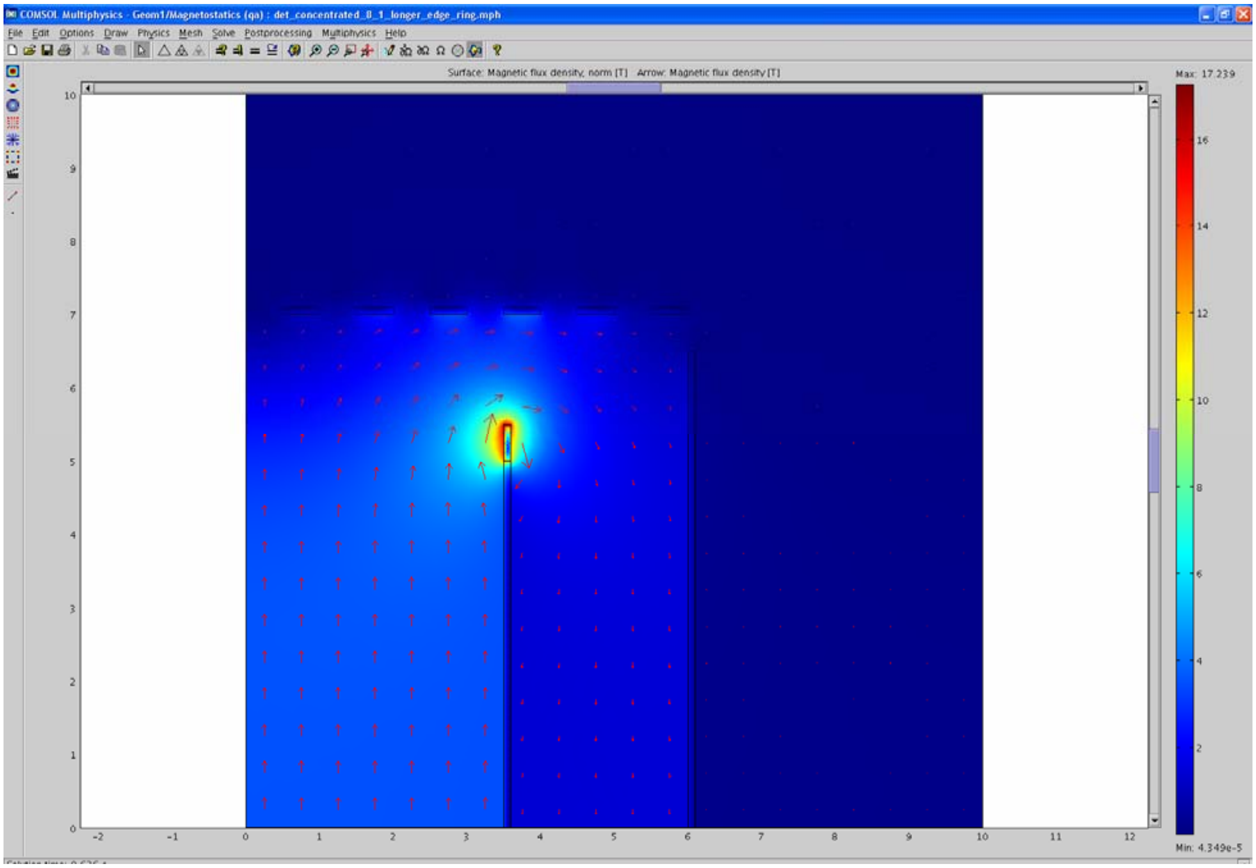
We can observe that the maximum flux density appears at the edge ring. This is not only caused by more current density but also that this is the singular point for this detector. So we can avoid shaping the field distribution using edge ring but use distributed winding in inner solenoid so that current density varies with location.

II. Original Current Distribution with High Field Peak

This case was studied using the current distribution as originally proposed [1] with sizing modification. If there is commercially available superconducting material to support high flux density, we could make a solenoid with such field distribution.

	Inner Solenoid	Edge Ring	Outer Solenoid
Current Density ($10^6 A/m^2$)	38.6	231.6	9.9

The maximum flux density is 17.2 T, which is quite high.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Min: 4.349e-5

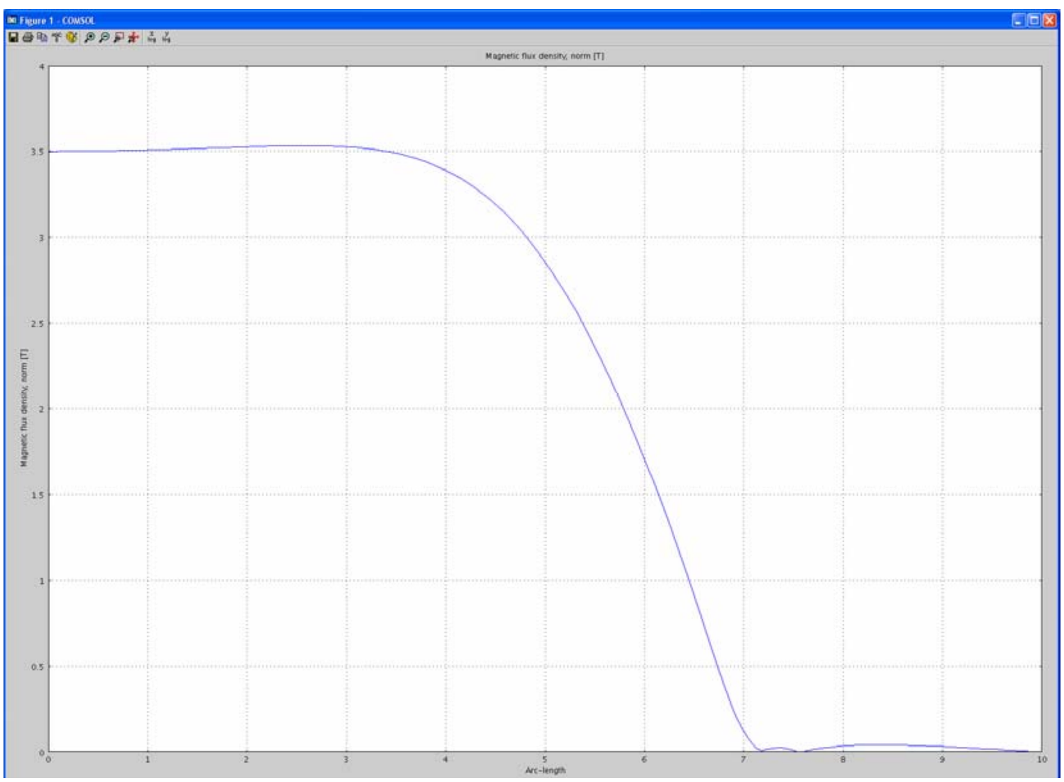
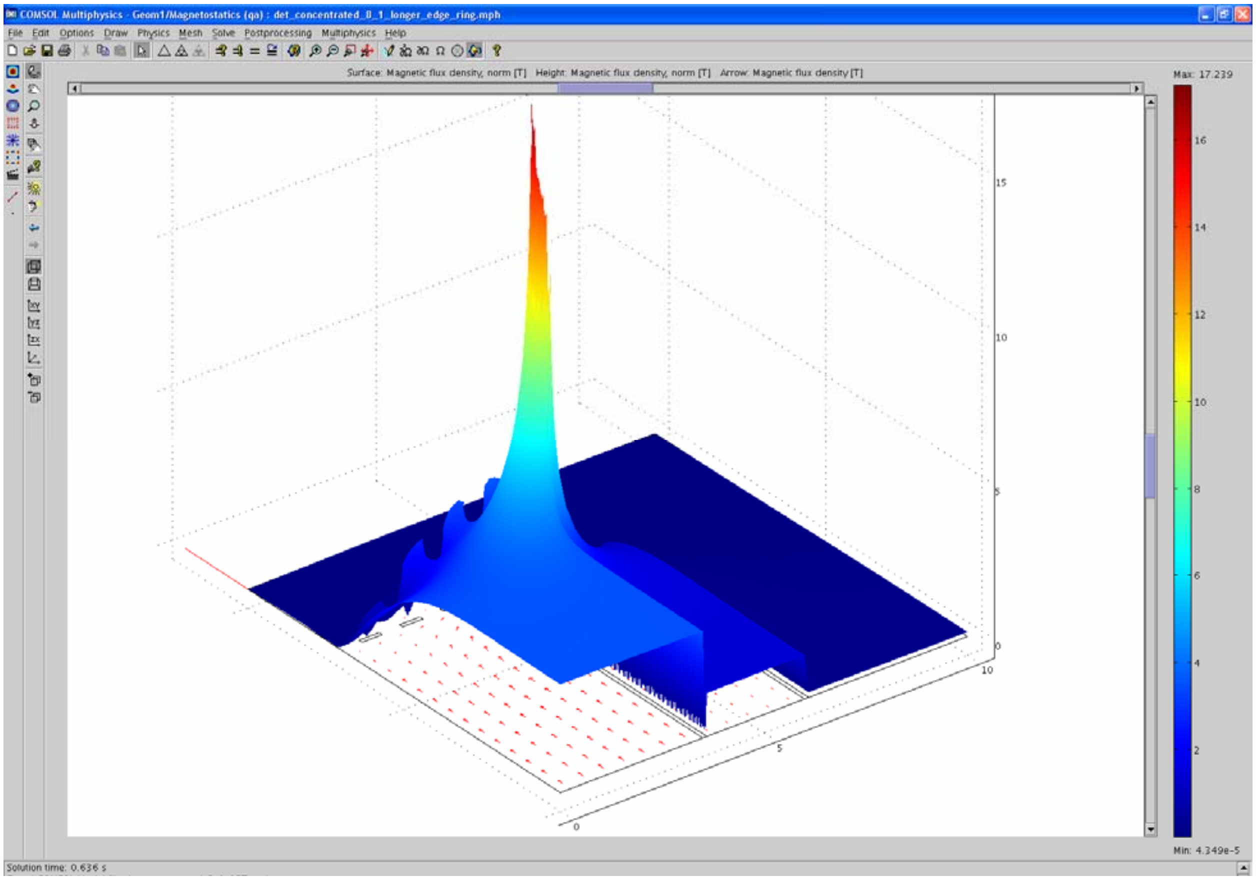


Figure 1 - COMSOL
Magnetic flux density, norm [T]
Magnetic flux density, norm [T]
Arc-length



III. Edge Ring Extended

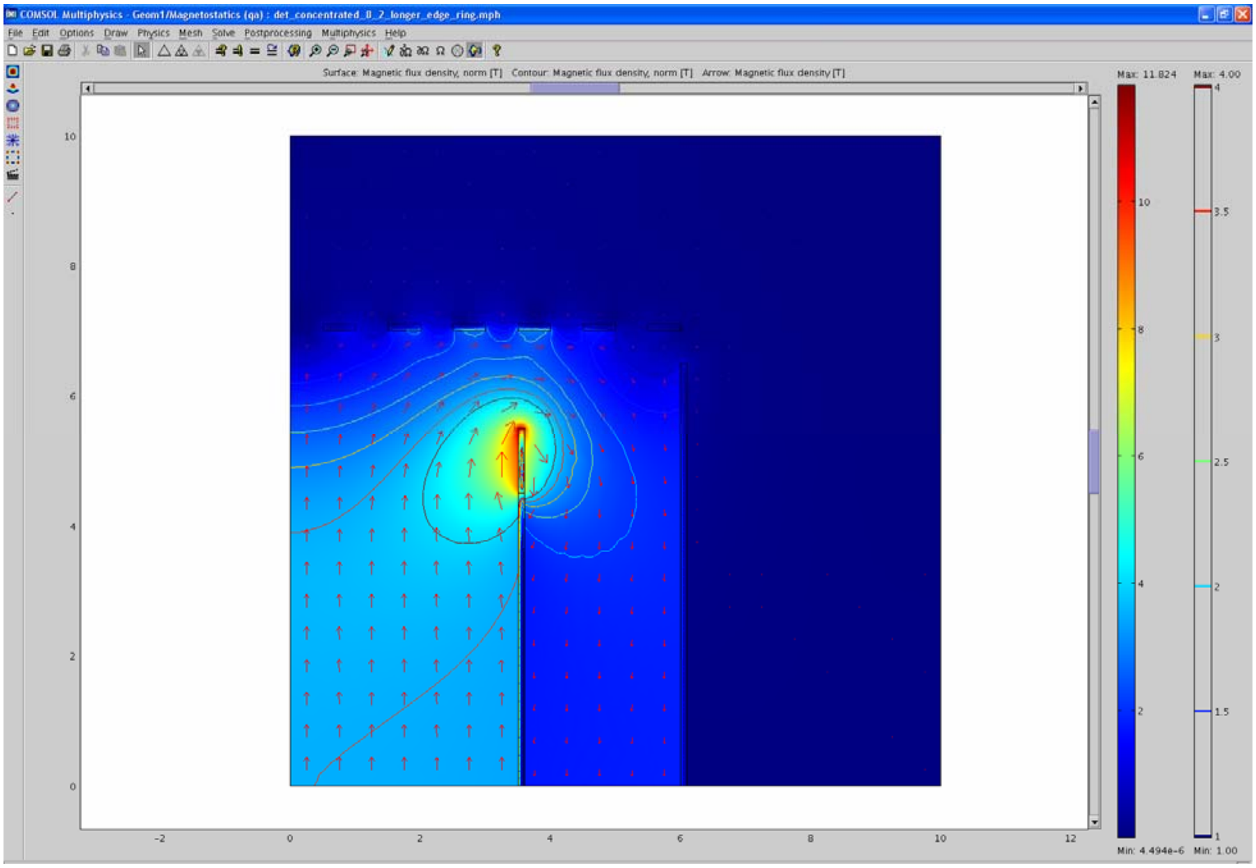
If the length of edge ring is increased, while keeping the total length of the inner solenoid coil winding the same, we could use less current density in the edge ring, Thus the maximum flux density could be reduced.

Simulation is done under following conditions. Jin=40.67 *10^6A/m^2

	Inner Solenoid	Edge Ring	Outer Solenoid
Current Density (10^6A/m^2)	40.67	134.2	14.08

	R1	R2	R3	R4	R5	R6
Factor based on Jin	0.4	0.5	0.6	0.7	0.4	0.1
Current Density (10^6A/m^2)	16.3	20.3	24.4	28.5	16.3	4.07

The maximum flux density is now 11.8 T.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Max: 4.00
Min: 4.494e-6
Min: 1.00

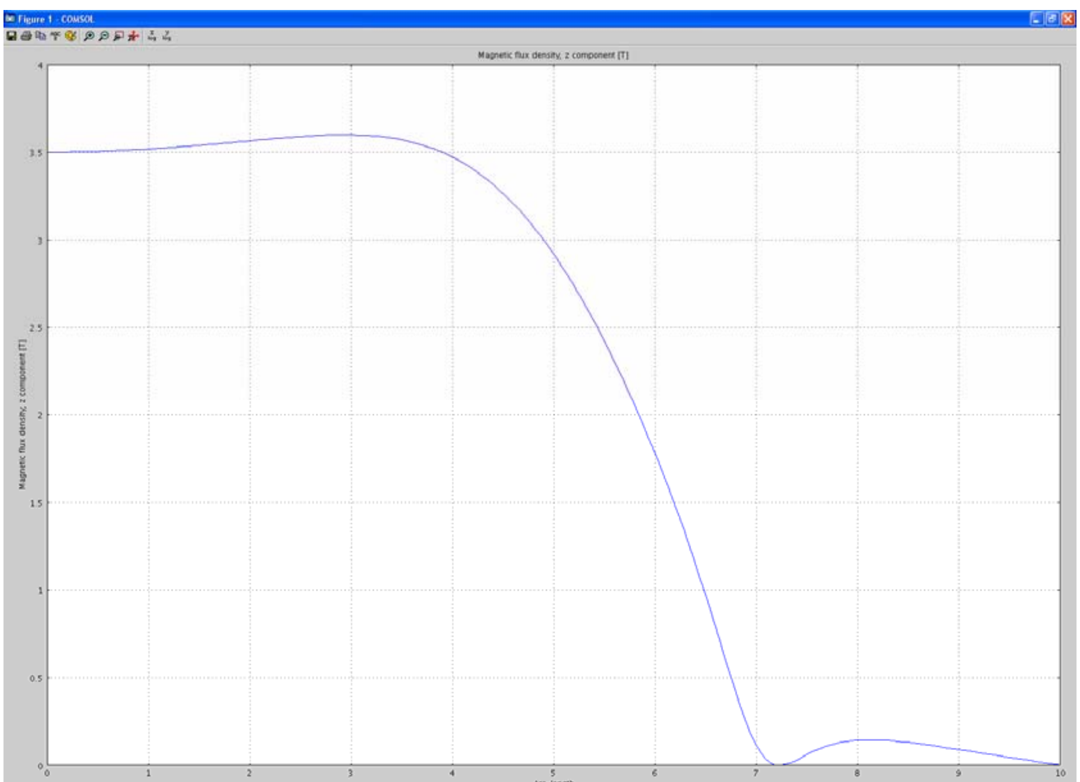
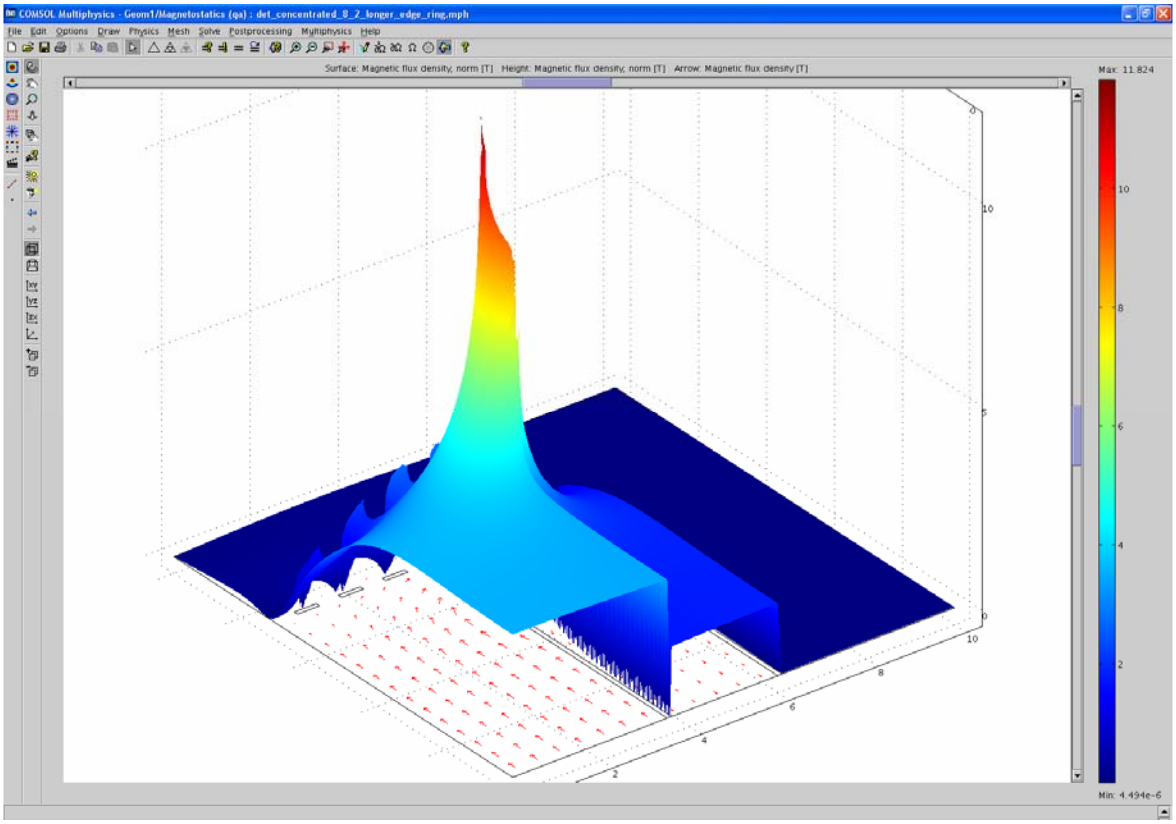
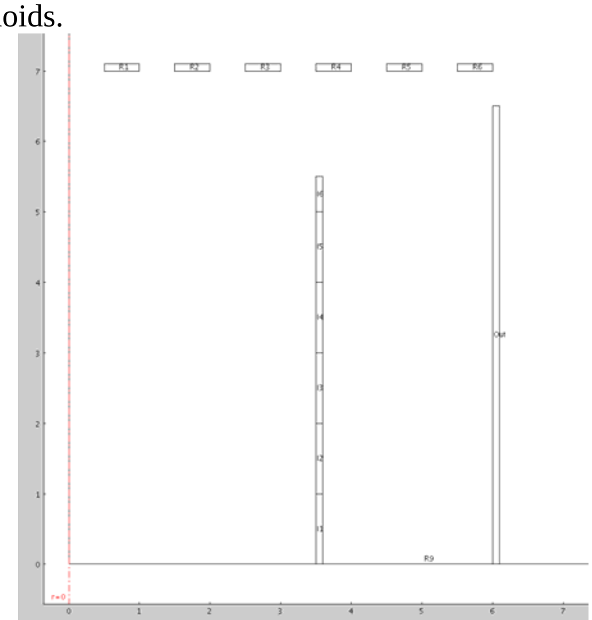


Figure 1 - COMSOL
Magnetic flux density, z component [T]
Arc-length



IV. Distributed Current Density Solenoid

An improved design that uses distributed current density is done. The inner solenoid is separated into finite segments, as show below. In this case, we used five segments; each one is 1 meter long, plus the half meter edge ring. Here the effect of singular point is eliminated by adding less current density in edge ring (I6) than the adjacent winding (I5). We can observe a more uniform field distribution along inner solenoids.



The current densities used in the simulation are shown below. The current density in inner solenoids are based on a unit current density Jin which is 24.4* 10^6A/m^2. Jring=-2.5* 10^6A/m^2

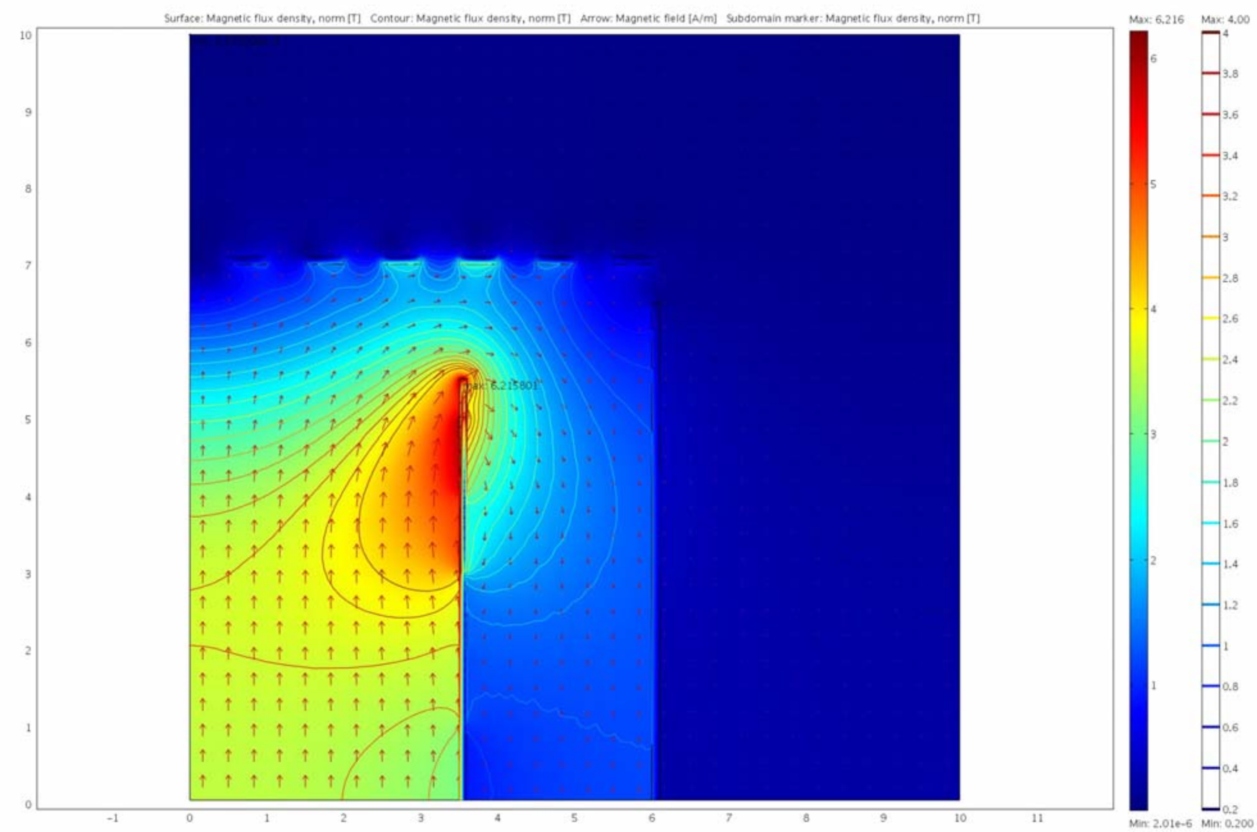
	I1	I2	I3	I4	I5	I6	Out
Factor based on Jin	1.3	1.5	1.6	2.5	3	2.2	-0.3
Current Density (10^6A/m^2)	31.7	36.6	39.0	61	73.2	53.7	-7.3

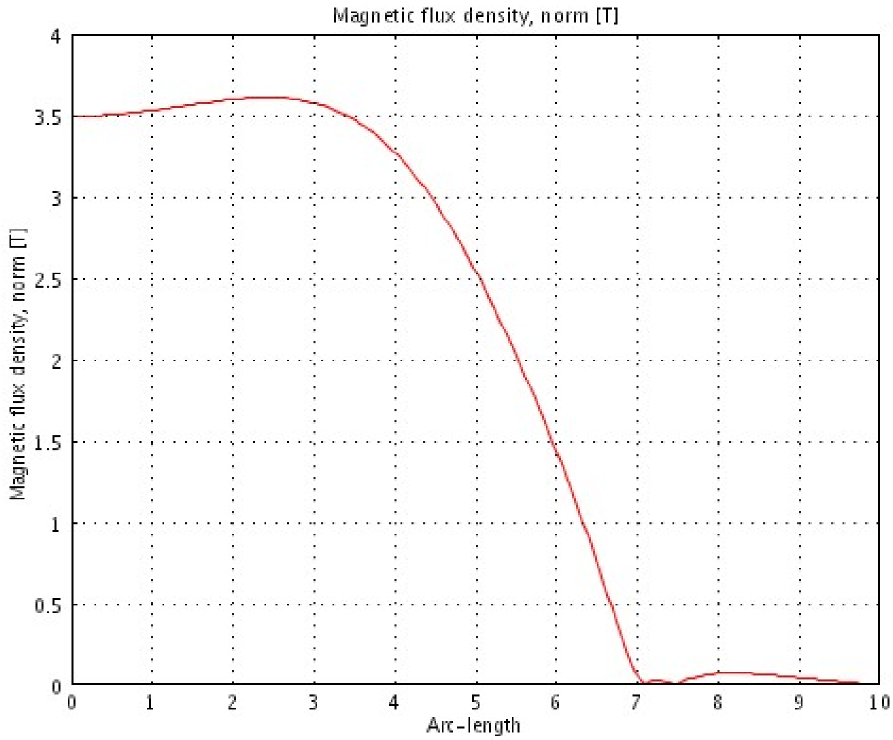
	R1	R2	R3	R4	R5	R6
Factor based on Jring	5	6	9	10	6	3
Current Density (10^6A/m^2)	12.5	15	22.5	25	15	7.5

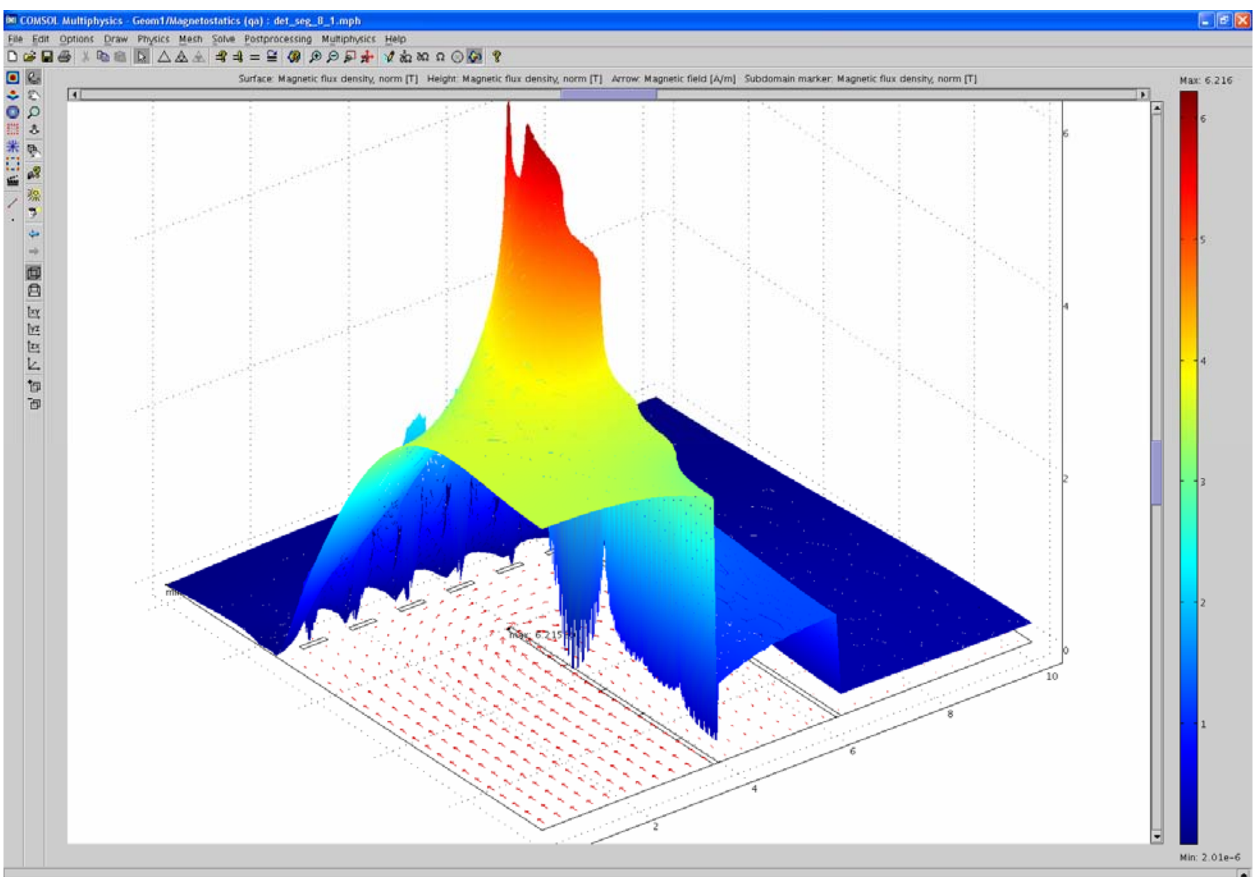
(signs all minus)

The maximum flux density is 6.2 T, as shown below.

This case is not optimized, but we think we can bring the maximum field around 6 Tesla with this method. The field inside TPC region could be made much more uniform by optimization and possibly with some small correction coils if needed.




Magnetic flux density, norm [T]
Magnetic flux density, norm [T]
Arc-length
0
0.5
1
1.5
2
2.5
3
3.5
4
0
1
2
3
4
5
6
7
8
9
10


COMSOL Multiphysics - Geom1/Magnetostatics (qa) : det_seg_8_1.mph
File Edit Options Draw Physics Mesh Solve Postprocessing Multiphysics Help
Surface: Magnetic flux density, norm [T] Height: Magnetic flux density, norm [T] Arrow: Magnetic field [A/m] Subdomain marker: Magnetic flux density, norm [T]
Max: 6.216
Min: 2.01e-6

References

[1] Detector Outline Document for the Fourth Concept Detector ("4th") at the International Linear Collider. 19 May 2006, at http://physics.uoregon.edu/lc/wwstudy/concepts/
[2] R. Yamada, A. Kikuchi et. al. "Feasibility Study of Nb_3Al Rutherford Cable for High Field Accelerator Magnet Application" presented at ASC06, and submitted on August 29, 2006. It will be published in IEEE Trans. Appl. Supercond.